Prediction of Lake Levels and Frequencies of Lake Andes Using WHAM, a Daily Time Step Water Budget Model

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ABSTRACT

A general investigation was completed in cooperation with the U.S. Fish and Wildlife Service (USFWS) to determine existing and future lake-level frequencies of Lake Andes in south-central South Dakota. Lake Andes is a natural glacial lake, similar to the Waubay Lakes in South Dakota, and it is influenced significantly by plains snowmelt, rainfall runoff and evaporation. Deterioration of its water control structures has rendered it difficult for USFWS to manage the lake for waterfowl production. As a result, USFWS is seeking to improve existing structures and raise levees for better lake management. A hydrologic model was created using the Wetland Hydrologic Analysis Model (WHAM). WHAM is a daily time-step water budget model developed by USACE Omaha District, which accounts for daily precipitation, evaporation, seepage, runoff, outflow, and wetland storage change. The model was calibrated to historic records from 1960 to 2002 with considerations for hydrologic trends in the glaciated watershed and changes to water control structures. The lake was initially simulated as three interdependent lake units; however, recent trends suggested that the lake levels in all units change simultaneously. From the calibrated model, 100 years of lake-level record were simulated under existing and future modified conditions, which included lowered outlet crest elevations. Lake-level frequency curves were developed from the simulated annual peak lake levels to provide USFWS with levee and outlet design recommendations.

PURPOSE OF STUDY

Lake Andes is a natural glacial lake located in south-central South Dakota. The U.S. Fish and Wildlife Service (USFWS) manages it as part of the Lake Andes National Wildlife Refuge. Figure 1 shows the location of Lake Andes in relation to other notable locations in South Dakota. Since Lake Andes is a natural lake, its water levels and volumes depend greatly on the fine balance of rainfall runoff, snowmelt runoff, lake evaporation, and lake outflows. Lake dikes and outlet structures constructed in the 1940s and 1960s enable USFWS to manage lake levels; however, reduced outflow capacities and structure deterioration have made it more difficult to manage lake levels in recent years. This, coupled with wet hydrologic periods in the 1980s, 1990s, and 2000s, has resulted in localized inundation of lake levee roads.

The Hydrology Section of the Omaha District conducted this study to provide technical assistance in fulfillment of USFWS goals. First, in seeking to upgrade dike roads, USFWS was in need of existing condition and future modified condition lake-level frequency relationships. Secondly, USFWS would like to better manage the lake for waterfowl production, which would require lake-level management at lower elevations and the ability to lower lake levels efficiently. USFWS has expressed interest in managing lake levels two to four feet lower than current levels. To assist USFWS in achieving these goals, lake-level frequency relationships were created from 100 years of simulated lake-levels for existing and future-modified lake conditions.

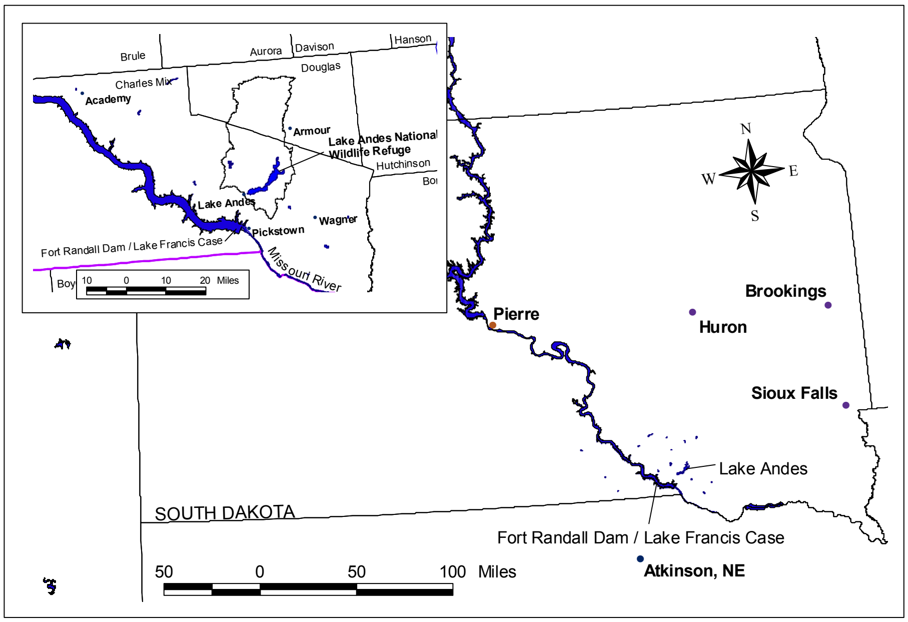

Figure 1 Lake Andes study site and sources of data.

METHODOLOGY

Although 34 years of lake levels were recorded at Lake Andes, a lake-level model was prepared to simulate 100 years of historic lake levels. The Wetland Hydrologic Analysis Model Version 3.4 (WHAM) was chosen for this project because it utilizes daily snow accumulation and snowmelt routines, which are important components of the glacial lake hydrologic cycle in South Dakota. Daily simulation data was compiled from local weather stations, while monthly hydrologic parameters were estimated using data from hydrologic studies in the region. Lake elevation area-capacity and outflow rating curves were constructed with USFWS information.

Model Description

The WHAM, was developed by the Omaha District of the Corps of Engineers to allow the continuous simulation of a lake or wetland and its adjacent watershed. WHAM is a daily time-step water budget model that accounts for daily precipitation, evaporation, seepage, runoff, outflow, and wetland storage change. WHAM uses a simple water budget principle (inflow = outflow + change in storage) to determine wetland or lake water surface elevations on a daily basis. WHAM requires inputs of daily precipitation, temperature and evaporation in text format. WHAM simulates watershed runoff using a simplified soil moisture index curve for determining excess precipitation and a daily time-step unit hydrograph. Additional inflows from gaged streams, pumps or diversions can also be specified. With the input of daily minimum and maximum temperature, WHAM may also simulate snow accumulation and snowmelt. Finally, WHAM determines outflow from the wetland or lake by an elevation-storage-outflow curve, with the capability to adjust outflow for tailwater conditions. Output may be written in text format or DSS.

Daily Data

WHAM requires daily inputs of precipitation, temperature, evaporation, and stream inflow. Temperature is required for the snow water equivalent and snowmelt functions. Daily simulation data excluding evaporation was obtained from the Pickstown, SD, weather station from 1952 to 2002, and was supplemented with data from Wagner, SD. Data for the period 1902 to1952 were obtained from measurements taken at Armour, SD.

Daily pan evaporation was obtained from Pickstown, SD, for the period 1951 – 2002. Since pan evaporation was not recorded during the ice-affected months, average monthly pan evaporation was estimated using the Penman equation distribution at Huron and Sioux Falls, SD (NWS Technical Report 34). Daily evaporation for the period 1902 – 1951 were obtained from estimates of monthly free water surface evaporation at Brookings prepared by Al Bender, SD State Climatologist. The Brookings data was adjusted so that the average annual evaporation used at Lake Andes matched the Pickstown average annual evaporation.

Monthly Hydrologic Parameters

Monthly hydrologic parameters required by the model include seepage rate, pan evaporation coefficient, outflow factors, and snowmelt rates. Evaporation factors were reduced from November through April to account for reduced evaporation caused by colder temperatures and ice cover. Snowmelt rates were adopted from the Waubay Hazard Mitigation Study.

Lake Drainage Areas and Capacity

The Lake Andes watershed is an undulating, hydrologically young plain in the Coteau de Missouri physiographic region of South Dakota. The watershed contains numerous small wetlands that may or may not contribute surface runoff to Lake Andes. Runoff contribution from these areas depends greatly on climatologic trends.

HEC Geospatial Hydrologic Modeling Extension (GeoHMS) aided in the delineation of the Lake Andes watershed from 1:24000 scale USGS digital elevation models. Since Lake Andes contained three lake units, the watershed was delineated into three subbasins. Table 1 provides total potential and generally noncontributing drainage areas for the watershed. Figure 2 is a schematic drawing of the Lake Andes watershed.

The U.S. Fish and Wildlife Service Lake Andes Refuge office provided elevation-area/capacity tables for the North, Middle, and South Units and Owens Bay.

Table 1 Potential Contributing and Noncontributing Subbasin Areas in the Lake Andes Watershed.

Subbasin	Potential Total Area (sq. mi.)	Generally Contributing Area (sq. mi.)	Generally Non-Contributing Area (sq. mi.)
North Unit	123.0	72.9	50.2
Middle Unit	54.6	43.3	11.3
South Unit	50.7	42.8	7.9
Owen's Bay	7.0	6.4	0.6
Total	**235.3**	**165.4**	**69.9**

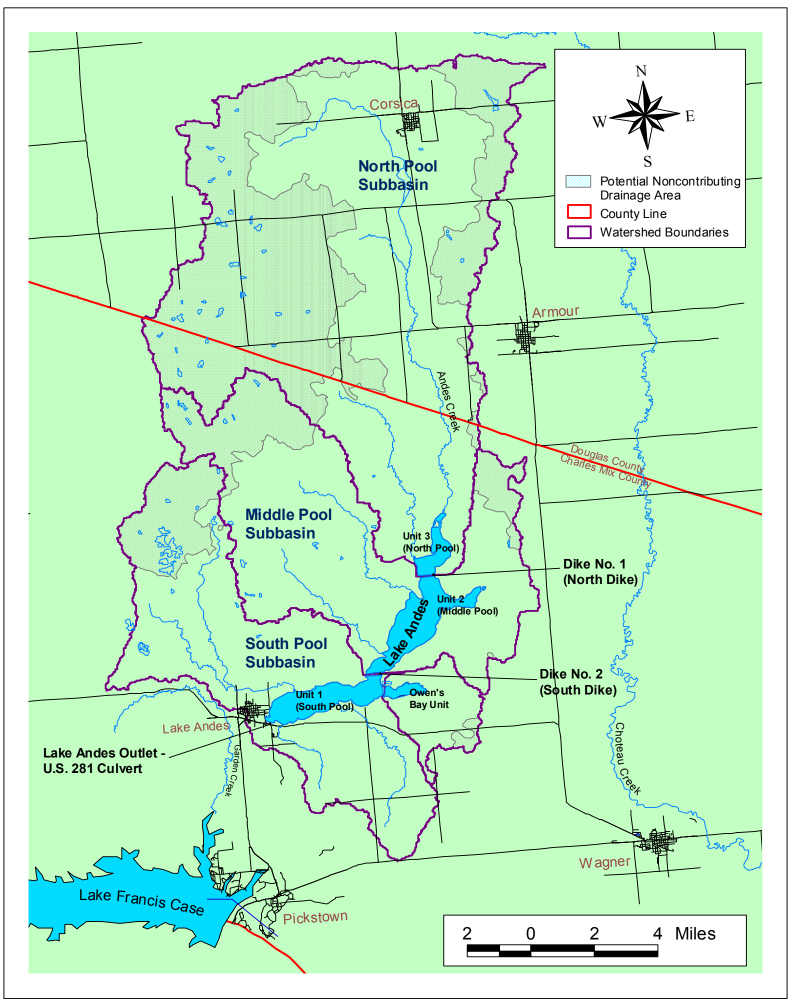

Figure 2 Lake Andes watershed and other important locations.

Spillway Discharge Relationships

Outflow rating relationships were determined for hydraulic structures located in the North, Middle and South Lake Units. The U.S. Fish and Wildlife Service provided all information regarding structure types and dimensions. Table 2 provides a description of each lake unit's hydraulic structures, dimensions, and crest elevations. Locations of important features including local roads, the dikes and the outlet structures are shown in Figure 2.

Table 2 Summary of lake unit outflow structures.

Lake Unit	Outlet Unit	Description	Dimensions	Crest (ft MSL)
North	Middle	Sharp-crested weir under North Dike low bridge cord	20-ft crest length	1437.25
		7 – corr pipe-arch culverts	58 x 36 inch	1436.40
		Broad crested dike/road	2500 ft crest length	1441.05
Middle	South	Sharp-crested weir under South Dike low bridge cord	20-ft crest length	1434.25
		Broad crested dike/road	3080 ft crest length	1439.25
South	Garden Creek	Normal depth crest under RR bridge	Bottom width = 27.70	1437.25
		Sharp-crested weir near inlet of US 281 box culvert	30.5 ft crest length 2 – 10 x 6 ft (span x rise) box culverts, flow elev. = 1433.55	1437.25

Each lake unit utilized a bridge or culvert and weir to control lake outflows. Discharge ratings for each weir were predicted with the sharp-crested weir flow equation (Eqn. 5-34 of King and Brater). Equation 5-50 of King and Brater was used to determine reductions in discharge due to submergence. Equations 6.32 and 6.33 of Sturm for flow through a submerged bridge opening were used to calculate flow through the bridge opening. Ratings were determined for various levels of outlet submergence. The Federal Highway Administration program HY8 was used to calculate rating curves for the seven pipe arches in the North Dike and the US 281 box culvert-rating curve at the outlet of the South Unit.

Road/dike-overtopping discharge was determined for the North and South Dikes using the broad-crested weir equation; but, it was not combined with the rating curves because it caused instability in the simulations.

Runoff Calculation

WHAM uses a simple soil moisture index (SMI) relationship to determine the fraction of precipitation converted to runoff based on an accounting of soil moisture as an index value. This method is based on the SMI method used in the Streamflow Synthesis and Reservoir Regulation (SSARR) Model, and more information may be found in Chapter 8 of EM 1110-2-1417.

Precipitation excess is based on families of calibrated or standard curves relating SMI and runoff percentage. The runoff percentage in this model is directly proportional to precipitation amount. The curve used in the model is based on one inch of rainfall, so for precipitation greater or less than one inch, the runoff factor is proportional to the rainfall amount. In snowfall situations daily evaporation is disregarded and precipitation is stored as snowpack. Snowpack is converted by a temperature dependent snowmelt rate to available moisture. WHAM distributes rainfall excess according to a daily time step unit hydrograph.

EXISTING LAKE LEVEL CONDITIONS

Model Calibration

Parameters from the Waubay Lakes WHAM Model were used as starting values for the combined model calibration effort. A rough sensitivity analysis performed on the WHAM model parameters revealed that Soil Moisture Index (SMI) was the most sensitive parameter, while the outflow-rating curve allowed finer adjustments in lake levels. Seepage rates and evaporation factors were also adjusted.

The existing conditions Lake Andes model was calibrated to approximately 34 years of monthly-recorded water surface elevations between 1960 and 2002. Observed water surface elevations were recorded on a prescribed day; therefore, they do not necessarily reflect peak lake-levels.

The total modeled period covers water years 1903 through 2002. To aid calibration, the Lake Andes model was divided into four time periods based upon physical changes to Lake Andes and patterns in the lake-level data collected since 1960. The time periods are:

Period A. (1903-1941) While there are no known lake-level readings for that period, drought years when the lake was dry were 1933, 1934 and 1939.

Period B. (1942-1966) This period occurred after lake dikes were constructed. A three lake-unit model was calibrated to observed data for the period 1960 – 1966.

Period C. (1967-1986) An additional water control structure was constructed to release water from the North Pool. The three-unit model was calibrated for all data available during that period.

Period D. (1987-2002) Water level measurements during this period suggested Lake Andes functioned as a continuous lake unit, though no operational activities were documented. A combined pool model was constructed for this period. Initial model parameters for all periods were derived from Period D.

Baseline Model

Baseline conditions at Lake Andes represent current operating trends and lake levels. The calibrated Combined Model from Period D was adopted as the Baseline Model, and 100 years of simulated lake levels were generated for the lake-level frequency analysis. Simulated Baseline Model water levels are shown in Figure 3.

Lake-Level Frequency Curve

The lake-level frequency curve was derived from the annual maximum lake levels using a graphical frequency analysis. An eye-fit curve was drawn through the Weibull plotting positions to represent the Baseline lake-level frequency relationship. Figure 4 includes a probability plot of the eye-fit curve and plotting positions. Table 3 summarizes lake-level elevations and exceedence frequencies from the Baseline frequency analysis.

Table 3 Lake Andes Baseline Conditions Model and coincident frequency analysis lake elevations.

Percent Chance Exceedence	Return Period	------- Lake Elevation, ft MSL -------	
		Baseline Frequency Analysis	Coincident Frequency Analysis
50.0	2	1436.80	1437.30
10.0	10	1439.70	1439.70
2.0	50	1441.00	1441.10
1.0	100	1441.80	1442.00
0.5	200	1442.20	1442.50
0.2	500	1442.70	1443.10

Coincident Lake-Level Frequency

Because annual maximum lake levels can be dependent upon the starting lake levels, and frequency analysis theory is based on the premise that all data used is independent, an additional analysis was completed to evaluate the effects of starting lake level on the computed frequency curve using a coincident frequency analysis. The coincident lake-level frequency relates the probability that events occur coincidently, or the probability that a specified event will occur given another event occurring. Simulations across a range of starting lake-level elevations were performed in which the starting elevation at the beginning of each water year was reset to a constant elevation. Starting lake-level elevations were 1426.0, 1428.0, 1430.0, 1432.0, 1434.0, 1436.0, 1438.0, 1440.0, 1442.0 ft MSL. A lake-level frequency curve was generated from each 100-year simulation in the set of simulations. The lake-level duration curve and family of lake-level frequency curves were combined to obtain the coincident lake-level frequency curve shown in Figure 4.

The most divergence occurs at frequencies higher than 0.30 and lower than 0.02; otherwise, lake-level frequencies did not vary substantially. Table 3 summarizes the difference in lake-levels exhibited by each curve at prescribed frequencies. Based on this analysis, the incidence of higher lake levels due to coincident occurrence of high starting lake-levels is very low, because high lake-levels have very low durations. Existing outflow structures limit high lake levels to low durations because these structures have the capacity to discharge large volumes of water very rapidly.

FUTURE MODIFIED CONDITIONS

The USFWS expressed an interest in managing the lake within a four-foot range for waterfowl production. This would require that lake levels could be lowered as much as four feet below the current invert elevation at the main Lake Andes outlet at U.S. Highway 281 (US 281). Lowering the invert elevation four feet would allow for the maintenance of lower average lake levels and increase the capacity of the main outlet, enabling water volumes to be flushed from the lake system in shorter periods of time.

Outlet Modifications

Conceptual modifications to the US 281 box culvert outlet included 2-ft and 4-ft lower crest elevations. The existing crest elevation of the outlet is 1437.25 ft MSL at the weir, yet the controlling section of the main outlet is the abandoned railroad bridge (footpath) located immediately upstream of the box culvert. Future-modified conditions would require improvement of the railroad bridge section so that the US 281 culvert and weir could control flow. In addition, it was assumed that the outflow channel downstream of US 281 would be improved to increase flow efficiency and reduce backwater.

In the 2-ft lower crest scenario, two feet of stoplogs were removed from the existing weir to establish the outlet crest at elevation 1435.25 ft MSL. The existing US 281 box culverts were not modified. Rating curves for the weir and box culverts were determined with the same methods as in the Combined Unit/Baseline Model.

In the 4-ft lower crest scenario, all stoplogs were removed from the weir, and only the unmodified U.S. 281 box culverts at crest elevation 1433.25 ft MSL remained. The outflow rating curves for the dual box culverts were determined using HY8.

Future Lake-Level Results

Two 100-year future-modified conditions simulations incorporated the 2-ft and 4-ft lowered crest models. Results of the simulations are plotted in Figure 5 for crest elevation 1435.25 ft MSL (2-ft lower) and 1433.25 ft MSL (4-ft lower).

Future Lake-Level Frequencies

Annual maximum lake levels of the future-modified conditions lake level scenarios were obtained from the 100-years of simulated lake elevations. Figure 6 is a probability plot of the eye-fit curve and plotting positions comparing the baseline and the future-modified conditions models. The 2-ft and 4-ft lower crest scenario curves have notably lower lake-level frequencies, with the 4-ft lower scenario being the lowest. Table 4 summarizes both baseline and future-modified lake levels at prescribed frequencies. A 2-ft outlet drop lowered the 50- and 100-year lake levels 2.0 and 1.8 feet, while the 4-ft outlet drop lowered the 50- and 100-year lake levels 2.7 and 2.4 feet, respectively.

Table 4 Recommended still pool lake level frequencies for existing and future management scenarios.

Percent Chance Exceedence	Return Period	------- Lake Elevation, ft MSL -------		
		Existing Pool-Level Management†	2.0-ft Lower Pool-Level Management	4.0-ft Lower Pool-Level Management
50.0	2	1436.80	1434.85	1433.25
10.0	10	1439.70	1436.85	1436.00
2.0	50	1441.00	1439.00	1438.30
1.0	100	1441.80	1440.00	1439.40
0.5	200	1442.20	1440.80	1440.20
0.2	500	1442.70	1441.60	1441.10

† Lake levels are from the Baseline Model frequency analysis.

SUMMARY

In the calibration, the model became unstable when the lake units released large discharges at levee overtopping. The daily time-step combined with the large discharges was the major culprit of this instability. Discharges at the upper end of the rating curves were scaled back to correct this instability.

The lack of water control structure operational data made it difficult to reach a more accurate calibration to the observed data without making some general assumptions. Since observed lake levels from 1987 through 2002 show that Lake Andes behaved as a single lake unit with infrequent higher levels at times in the North Unit, it was reasonable to use a combined unit approach to model the three-unit lake system.

Maximum coincident lake levels occurring at the 10%(10-year), 2%(50-year), and 1%(100-year) frequencies are 1439.70, 1441.10, and 1442.00 ft MSL, respectively. Existing road elevations reported in NGVD 1929 as-built elevations are 1441.05 ft MSL on the North Dike, and 1440.25 ft MSL on the South Dike. Static pool elevations at the 1% frequency will overtop the dikes, while 2% frequency elevations may partially overtop the dikes under current operating conditions.

Future modified conditions of the Lake Andes outlet at the U.S. 281 box culverts could include a 2-ft lowering of the weir inlet elevation to 1435.25 ft MSL, or a 4-ft lowering of the inlet elevation to 1433.25 ft MSL (complete stoplog removal). Operating Lake Andes at lower levels would substantially affect overall lake-levels and the lake-level frequencies. Maximum lake levels that could occur under the 2-ft lower crest elevation at the 10%(10-year), 2%(50-year), and 1%(100-year) frequencies are 1436.85, 1439.00, and 1440.00 ft MSL, respectively. Maximum lake levels that could occur under the 4-ft lower crest elevation at the 10%(10-year), 2%(50-year), and 1%(100-year) frequencies are 1436.00, 1438.30, and 1439.40 ft MSL, respectively.

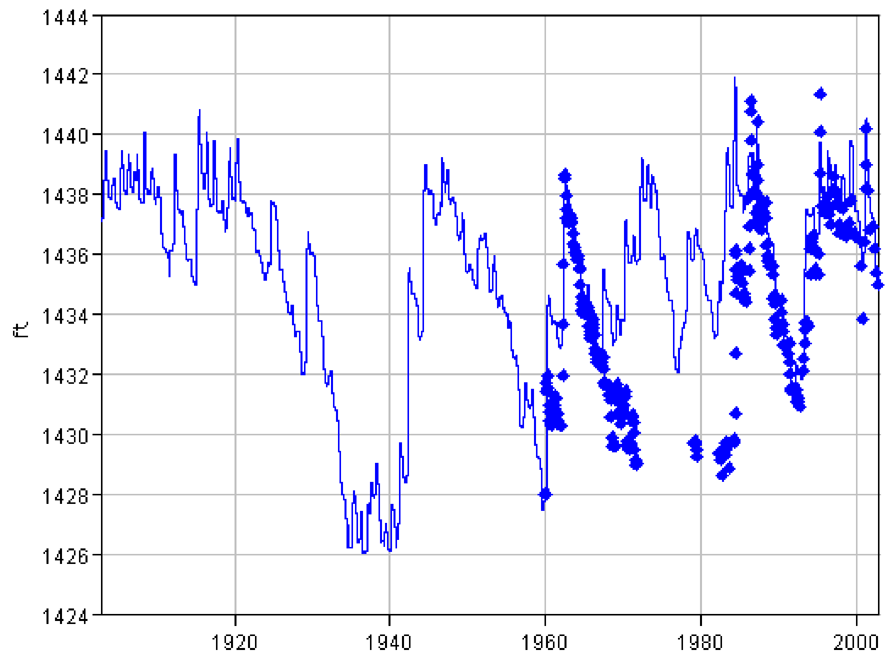

Figure 3 Lake Andes Baseline Model simulated water levels (solid line) and observed water surface elevations (symbols) from 1902 through 2002.

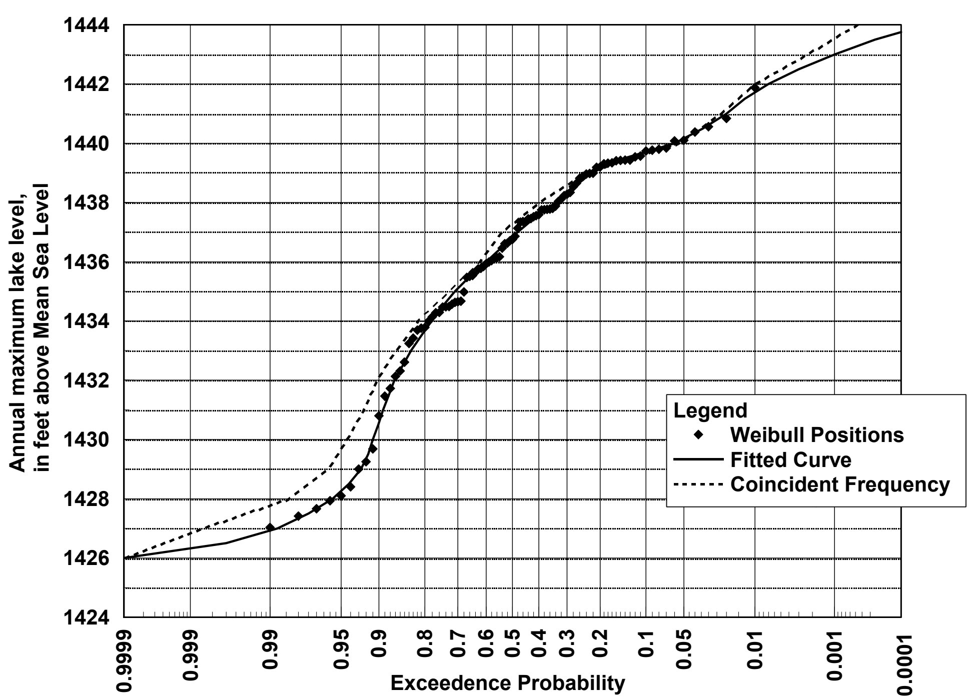

Figure 4 Lake Andes Baseline Model lake-level and coincident lake-level frequencies with plotting positions.

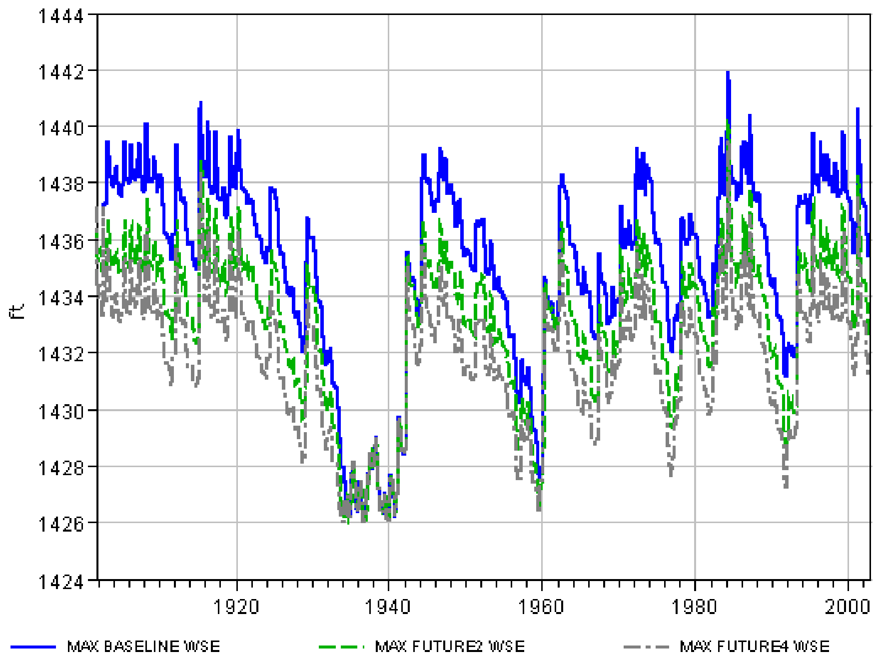

Figure 5 Comparison of Baseline Model and Future-Modified Conditions (2-ft & 4-ft lower crests) lake levels.

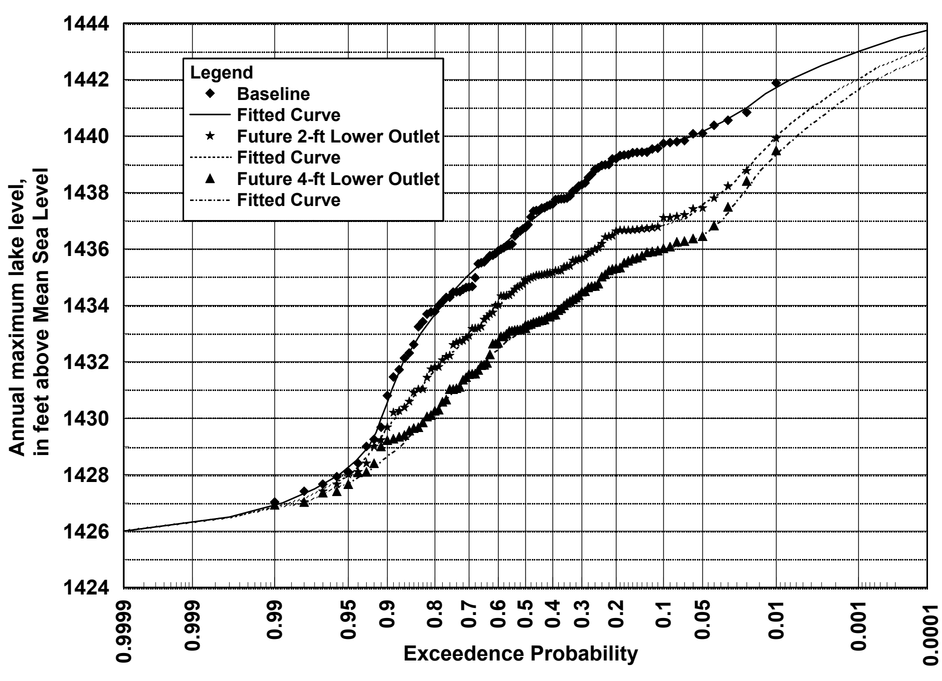

Figure 6 Baseline and future modified condition lake-level frequency curves (2-ft and 4-ft lower outlets) and plotting positions.

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